FINAL REPORT

EMBEDDED FUNCTION METHODS FOR COMPRESSIBLE HIGH SPEED TURBULENT FLOW

NASA LANGLEY RESEARCH CENTER
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J. D. A. Walker
Department of Mechanical Engineering and Mechanics
Lehigh University

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This is Final Report on the work performed on the Grant "Embedded Function Methods for Compressible High Speed Turbulent Flow" carried out at Lehigh University during the contract period from September, 1987, to October of 1991. Work has continued at Lehigh on this project on an unfunded basis to the present. The original proposed work had two separate thrusts which were associated with developing embedded function methods in order to obviate the need to expend computational resources on turbulent wall layers in Navier Stokes and boundary-layer calculations. Previous work on the incompressible problem had indicated that this could be done successfully for two-dimensional and three-dimensional incompressible flows. The central objective here was to extend the basic approach to the high speed compressible problem. In the program the basic theory and algorithms were to be developed under the direction of Professor J. D. A. Walker at Lehigh University. An implementation of these algorithms was then to be carried out at United Technologies Research Center by Mr. Greg Power in a Navier-Stokes code from NASA Langley.

The Lehigh portion of the project has been successfully completed and the publications associated with this work are listed subsequently in this report. Reprints of published papers are attached and copies of papers in review will be sent in due course. The United Technologies portion of the project was originally oriented towards implementation of the algorithms into a specific code called NASCRIN. This is an explicit Navier Stokes code which uses the Baldwin-Lomax turbulence model and requires substantial computational resources and computing times. After a considerable amount of calculations at United Technologies, it was decided that this explicit code was probably not the best computer algorithm to implement the embedded function method. More recent Navier Stokes codes typically employ implicit methods which are much more efficient and better suited to the embedded function approach. This was subsequently demonstrated in studies of incompressible flow by the present author. By the end of the first year it was decided that efforts should be switched into developing the method into the more modern implicit codes currently in use at NASA-Langley. Unfortunately, a budget cut necessitated termination of the United Technologies portion of the contract at the end of the first year.

This report describes principally the theoretical and computational work carried out at Lehigh University by Professor J. Y. Kazakia and J. D. A. Walker. A Ph.D. candidate, Mr. Jun He, received his doctorate for the work in June of 1993.

At the outset of the work it was understood that there were a number of unresolved issues in high speed compressible flow and the scaling laws for this environment are, at best, controversial. It has been common practice to take incompressible turbulence models and apply them to the high speed compressible regime almost without modification. The development of embedded function methods to remove the necessity to: (1) have separate turbulent models for the turbulent wall layer and (2) actually calculate the details of the turbulent wall layer. The embedded function methodology has been successfully applied to incompressible turbulent flows. The

approach involves a rather subtle match between an asymptotic solution for the wall layer and an outer numerical scheme. It is crucial to be able to develop self-consistent turbulent models and to appreciate the correct asymptotic scaling laws for high-speed compressible flow in order to carry out this approach.

The first work carried out at Lehigh University and reported by He et al. [1990] undertook an asymptotic analysis of the compressible turbulent boundary-layer equations. A number of different approaches were considered and, finally, a general method based introducing the Howarth-Dorodnitsyn variable was developed. A variety of modification of standard low-speed compressible algebraic turbulence models were investigated, and self-consistent modification of the Cebeci-Smith and Baldwin-Lomax models were eventually devised. Comparisons with measured experimental data showed very close agreement with the theory and were very encouraging. Preliminary implementation of the algebraic models in a boundary-layer prediction method was carried out by Degani et al. [1991]. This paper showed that the general approach could be successfully carried out in the high speed compressible environment provided the correct scaling laws were introduced.

Turbulence data for the total enthalpy profiles in an adiabatic flow shows that the enthalpy develops an s shaped pattern with an overshoot above the mainstream value in the outer part of the boundary layer. This influence is associated with viscous dissipation and is not accounted for in any other current turbulence theory. A systematic approach for adiabatic walls was developed by He et al. [1992], and an expression for the recovery factor was developed from first principles. Comparisons with the experimental data were, again, very favorable. A new form of the turbulence model was obtained in this paper, and the theory was potentially thereby extended to higher Mach number flows. In the original work reported by He et al. (1990), a program was developed to calculate self-similar velocity and total enthalpy profiles in flows with and without heat transfer. In the data comparisons, some discrepancies were noted, especially for high Mach number flows between the reported experimental values of skin friction and the calculated results. Often the experimental values are inferred indirectly and there was, therefore, some uncertainty about the accuracy of the so-called "measurements". Upon re-examination of the theory, it was decided to treat the wall layer in a somewhat different manner and introduce a reference density into the formulation. The reference density is essentially equivalent to an average density across the wall layer and is generally characteristic of the wall layer density, as well as the density near the inner edge of the outer layer. The analysis was repeated as well as comparisons with all of the available experimental data. The result is the paper by He et al. [1994a], which has been favorably reviewed for the *Journal of Fluid Mechanics*, with the revised version now currently in review. Results for the adiabatic supersonic boundary layer have been reported in detail by He et al. [1994b]. These two papers establish a firm basis for asymptotic theories of supersonic boundary layers and provide a foundation for consideration of changes in structure that occur in the hypersonic regime. The theory developed is, for the most part, for general algebraic models, but detailed modifications have been shown for both the Cebeci-Smith and Baldwin-Lomax models. A recent note by He and Walker [1994] has shown that both models are

equivalent in the limit of small Mach numbers, provided the constants are selected in a certain way in the Baldwin-Lomax model.

The computer codes developed under this contract to predict profiles in a high speed compressible flow have been distributed to United Technologies Research Center and were taken to NASA Langley in 1991. Refined versions of these codes are available upon request from the author. Publications associated with this grant are listed subsequently with reprints attached.

Graduate Students

Dr. Jun He   Ph.D. awarded June 1993   "Asymptotic Structure of Supersonic Turbulent Boundary Layers", Department of Mechanical Engineering and Mechanics, Lehigh University

Publications Associated with Grant

1. J. He, J. Y. Kazakia and J. D. A. Walker 1990 "Embedded Function Methods for Supersonic Turbulent Boundary Layers", AIAA Paper 90-0306, 28th Aerospace Sciences Meeting, Reno, NV, January.

2. A. T. Degani, J. D. A. Walker, S. Ersoy and G. Power 1991 "On the Application of Algebraic Turbulence Models to High Mach Number Flows", AIAA Paper 91-0616, 29th Aerospace Sciences Meeting, Reno, NV, January.

3. J. He, J. Y, Kazakia, A. I. Ruban and J. D. A. Walker 1992 "An Algebraic Model for Dissipation in Supersonic Turbulent Boundary Layers", AIAA Paper 92-0311, 30th Aerospace Sciences Meeting, Reno, NV, January.

4. J. He, J. Y. Kazakia and J. D. A. Walker 1994a "An Asymptotic Two-Layer Model for Supersonic Turbulent Boundary Layers", submitted to *Journal of Fluid Mechanics*, favorably reviewed, revised paper currently in review.

5. J. He, J. Y. Kazakia, A. I. Ruban and J. D. A. Walker 1994b "A Model for Adiabatic Supersonic Turbulent Boundary Layers", submitted to *Theoretical and Computational Fluid Dynamics*, in review.

6. J. He and J. D. A. Walker 1994 "A Note on the Baldwin-Lomax Turbulence Model", submitted to *Journal of Fluids Engineering*, in review.

7. J. He 1993 "Asymptotic Structure of Supersonic Turbulent Boundary Layers", Ph.D. Thesis, Lehigh University.